Energy Budget of Nonlinear Internal Waves near Dongsha

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LONG-TERM GOALS

Our long-term scientific goal is to understand the mechanisms by which mixing occurs in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is our particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. In this study, our broad focus is on the energy sources of nonlinear internal waves (NLIWs) in a complex environment of strong internal tides and abrupt topography (continental shelf and slope). We expect a rapid evolution of internal tides and NLIWs, and aim to understand their dynamics, energy cascade, and role in mixing.

OBJECTIVES

The primary objectives of this project are 1) to identify the generation site and understand the generation mechanism of NLIWs, 2) to understand the evolution of NLIWs as they interact with abrupt topography, 3) to quantify the energy budget and energy cascade from internal tides to NLIWs, and 4) to quantify the seasonal variation of the energy of NLIWs near Dongsha Plateau in the northern South China Sea (SCS). Our particular interest is to understand the energy cascade from barotropic tides, internal tides, and NLIWs to turbulence mixing in the northern SCS, and to understand the evolution of NLIWs interacting with the shoaling continental slope.

APPROACH

Our approach is to take direct observations of NLIWs near Dongsha Island where NLIWs are often captured in satellite images. Primary platforms include an ADV Lagrangian Float, an array of bottom-mounted ADCP moorings, and shipboard EK500, marine radar, ADCP, and CTD. Our main goals are to quantify the energy budget and evolution of NLIWs across the rapidly shoaling continental slope and the gentle plateau near Dongsha Island and to quantify seasonal variations of NLIW characteristics.

WORK COMPLETED

We have completed three components of this observational experiment: (1) pilot observations in 2005, (2) extended observations in 2006–2007, and (3) intensive observations in 2007.

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Pilot Observations (April 2005)

In April 2005 we conducted a two-week observational experiment near Dongsha (Fig. 1). Large-amplitude NLIWs, greater than 150 m, and strong turbulence mixing were observed by the Lagrangian float and shipboard sensors including ADCP, CTD, EK500, and X-band marine radar. Combined remote sensing and in-situ measurements provided detailed properties of large-amplitude NLIWs.

Extended ADCP Observations (June 2006–May 2007)

An array of three ADCP moorings was deployed along the prevailing path of NLIWs near Dongsha in June 2006. Three ADCPs were serviced once and recovered in May 2007. Two of three moorings took velocity measurements for about 11 months. These long-term observations of NLIWs allow us to (1) quantify the seasonal variation of NLIW energy, (2) map the geographical distribution, (3) better understand the dynamics of NLIW evolution over the shoaling topography, and (4) assess the model prediction skill of NLIWs.

Intensive Observations (April–May 2007)

We participated in the multi-ship intensive observation experiment near Dongsha in April–May 2007. Another bottom-mounted ADCP mooring was deployed on the Dongsha plateau to help acousticians understand the effects of NLIWs on acoustic propagation. Our main goals were to understand the interaction of internal waves, including internal tides and NLIWs, with the rapidly shoaling continental slope, and to quantify the energy budget of internal waves near Dongsha. Our primary instruments included Scripps Institution’s fast CTD profiler, and shipboard ADCP, CTD, EK500, and marine radar. During the cruise two McLane moored profilers were deployed, one on the continental slope and the other on the Dongsha Plateau (Fig. 2).

In 2007–2008 we began processing CTD and ADCP data collected during the intensive observations in April–May 2007, and processing ADCP data taken in the extended mooring observations on the slope of Dongsha Plateau, June 2006–May 2007. Our main focus in 2008 was to develop schemes to compute (1) the total kinetic energy of NLIWs, (2) the propagation speed and direction of NLIWs, and (3) the potential energy of NLIWs using moored ADCP data.

The average wave speed between moorings may be estimated by the difference of arrival times of NLIWs on moorings across the Dongsha Plateau. The extrapolation of the wave speed to an individual mooring site could be seriously inaccurate because NLIW propagation speed decreases dramatically over the shoaling slope and across the three mooring sites. Therefore, it is necessary to develop independent schemes to estimate propagation velocity, using ADCP measurements at individual mooring sites to compute the NLIW energy flux at mooring sites.

In 2008–2009 we continued our analysis to (1) estimate propagation speed and direction of NLIWs using ADCP measurements at individual mooring sites, (2) describe trapped core properties within NLIWs propagating on the slope, (3) quantify the intra-annual variations of internal tides and NLIWs, and (4) quantify pressure perturbations induced by NLIWs.

RESULTS

Supported by this project, four papers have been published (Lien et al. 2005, Chang et al. 2006, Moore and Lien 2007, Chang et al. 2008), two papers (Chang et al. 2010, Lien et al. 2010) are under review, and two more papers are in preparation. There are many co-authored papers. The two papers under review are summarized as follows.

<u>Nonlinear internal wave properties estimated with moored ADCP measurements</u> (M.-H. Chang, R.-C. Lien, Y. J. Yang, and T. Y. Tang, submitted to *J. Atmos. Ocean. Tech*., 2010)

A method is developed to estimate nonlinear internal wave (NLIW) vertical displacement, propagation direction, and propagation speed from moored ADCP velocity observations. The method is applied to three sets of bottom-moored ADCP measurements taken on the continental slope in the South China Sea in 2006–2007. NLIW vertical displacement is computed as the time integration of ADCP vertical velocity observations corrected with the vertical advection of the background flow by the NLIW. NLIW vertical currents displace the background horizontal current and shear by ~150 m. NLIW propagation direction is estimated as the principal direction of the wave-induced horizontal velocity vector. And propagation speed is estimated using the continuity equation in the direction of wave propagation, assuming the wave horizontal spatial structure and propagation speed remain constant as the NLIW passes the mooring, typically O(10 min). These NLIW properties are estimated simultaneously and iteratively using the ADCP velocity measurements corrected for their beam-spreading effect. For most cases, estimates converge to within 3% after four iterations. This method of extracting NLIW properties from velocity measurements is further confirmed using NLIWs simulated by the fully nonlinear Dubreil–Jacotin–Long model. Estimates of propagation speed using the ADCP velocity measurements are also in good agreement with those calculated from NLIW arrival times at successive moorings. This study concludes that velocity measurements taken from a single moored ADCP can provide useful estimates of vertical displacement, propagation direction, and propagation speed of large-amplitude NLIWs.

<u>Trapped core formation within a shoaling nonlinear internal wave</u> (R.-C. Lien, E. A. D'Asaro, F. Henyey, M.-H. Chang, T. Y. Tang, and Y. J. Yang, submitted to *J. Phys. Oceanogr*., 2010)

Large-amplitude (100–200 m) non-linear internal waves (NLIWs) were observed on the continental slope in the northern South China Sea nearly diurnally during the spring tide. The evolution of one NLIW as it propagated up the continental slope is described. The NLIW arrived at the slope as a nearly steady-state solitary depression wave. As it propagated up the slope, the wave propagation speed C decreased dramatically from 2 m s^{-1} to 1.3 m s^{-1}, while the maximum along-wave current speed $U_{\max}$ remained constant at 2 m s^{-1}. As $U_{\max}$ exceeded C, the NLIW reached its breaking limit and formed a subsurface trapped core with closed streamlines in the coordinate frame of the propagating wave. The trapped core consisted of two counter-rotating vortices feeding a jet within the core. It was highly turbulent with 10–50-m density overturnings caused by the vortices acting on the background stratification, with an estimated turbulent kinetic energy dissipation rate of $O(10^{-4})$ W kg^{-1} and an eddy diffusivity of $O(10^{-1})$ m^2 s^{-1}. The core mixed continuously with the surrounding water resulting in a wake of mixed water, observed as a salinity anomaly on isopycnals (Fig. 3). As the trapped core formed, the NLIW became unsteady and dissipative, and broke into a large primary wave and a smaller wave. These processes of wave fission and dissipation continued so that the NLIW evolved from a single deep-water solitary wave as it approached the continental slope into a train of smaller waves on the Dongsha Plateau.

IMPACT/APPLICATION

Our analysis concludes that NLIWs evolve rapidly across the upper flank of the continental slope and the Dongsha Plateau via complicated processes, e.g., the formation of trapped cores, and the development of wave trains. These processes are responsible for the strong dissipation of NLIWs in the SCS. Our analysis of combined remote sensing and in-situ measurements yields a model to predict NLIW properties applicable to satellite observations. The newly developed scheme to estimate NLIW wave speed and direction is useful for quantifying wave properties, including energy flux, using a single bottom-mounted ADCP. Further long-term observations of NLIWs in the vicinity of Dongsha Plateau are under way and will provide a better prediction of NLIWs in the SCS.

RELATED PROJECTS

<u>Study of Kuroshio Intrusion and Transport Using Moorings, HPIES, and EM-APEX Floats (N00014-08-1-0558) as a part of QPE DRI</u>: The primary objectives of this observational program are 1) to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), 2) to identify the generation mechanisms of the Cold Dome often found on the SECS, 3) to quantify the internal tidal energy flux and budgets on the SECS and study the effects of the Kuroshio front on the internal tidal energy flux, 4) to quantify NLIWs and provide statistical properties of NLIWs in the SECS , and 5) to provide our results to acoustic investigators to assess the uncertainty in acoustic predictions. Results of the NLIWI DRI will provide a better understanding of the dynamics of NLIWs that have strong effects on acoustic propagation and sonar performance.

<u>Process Study of Oceanic Responses to Typhoons using Arrays of EM-APEX Floats and Moorings (N00014-08-1-0560) as a part of ITOP DRI</u>: We study the dynamics of the oceanic response to and recovery from tropical cyclones in the western Pacific using long-term mooring observations and an array of EM-APEX floats. Pacific typhoons may cause cold pools on the continental shelf of the East China Sea.

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R.-C. Lien, E. A. D'Asaro, F. Henyey, M.-H. Chang, T. Y. Tang, and Y. J. Yang, Trapped core formation within a shoaling nonlinear internal wave, submitted to *J. Phys. Oceanogr*., 2010.

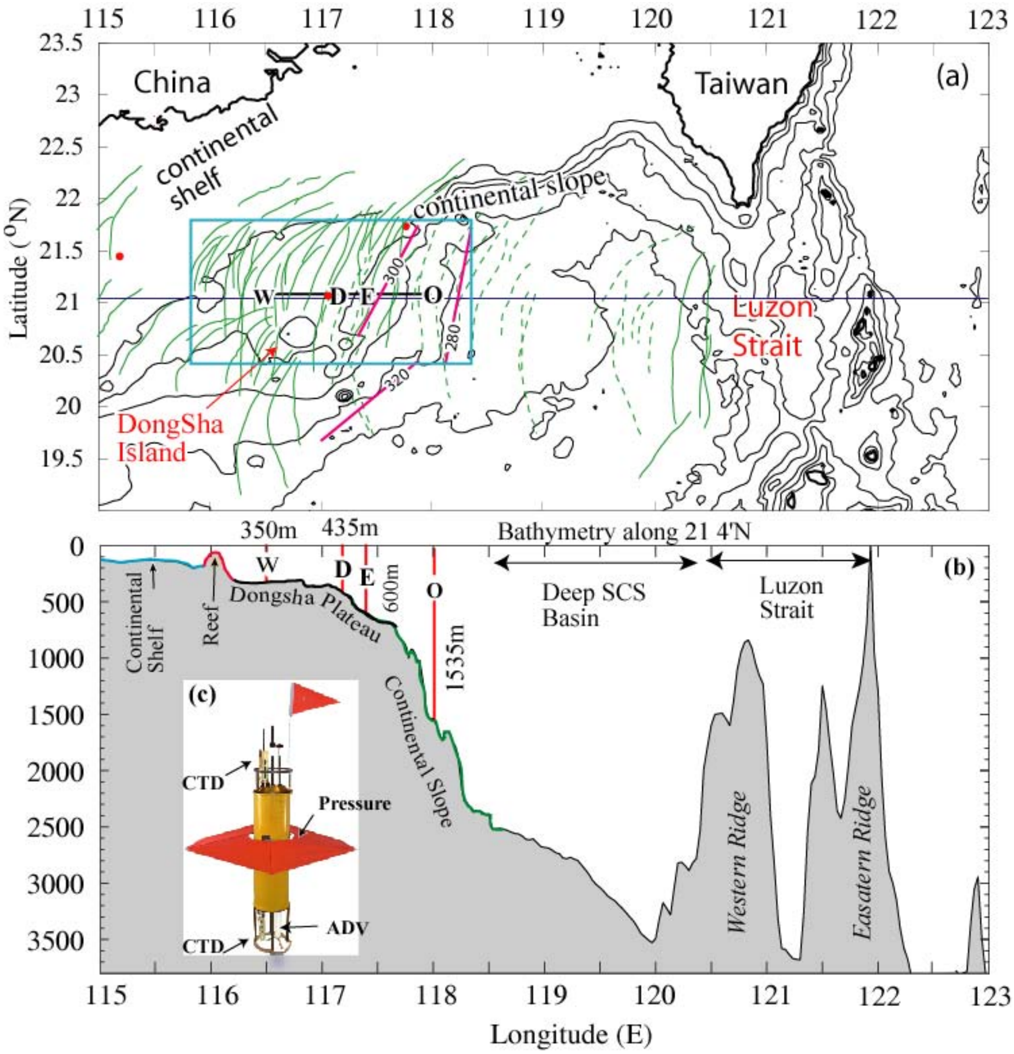

Figure 1. (a) Map of the northern South China Sea, and (b) bottom bathymetry along 21°4'N. In (a) green curves represent surface signatures of NLIWs identified in satellite images (Zhao et al., 2004), dashed for single-depression waves and solid for multiple wave packets. The blue box delineates the area where multiple wave packets are mostly found. Four primary stations in our April–May 2005 cruise are labeled as O, E, D, and W. Shipboard and float measurements were taken along O-E-D-W. Three magenta curves illustrate isobaric orientations on the continental slope. In panel (b) two submarine ridges in the Luzon Strait are labeled. They are responsible for generating strong internal tides. Depths at four primary stations are also labeled. The inset (c) shows the Lagrangian float and sensors equipped on the float.

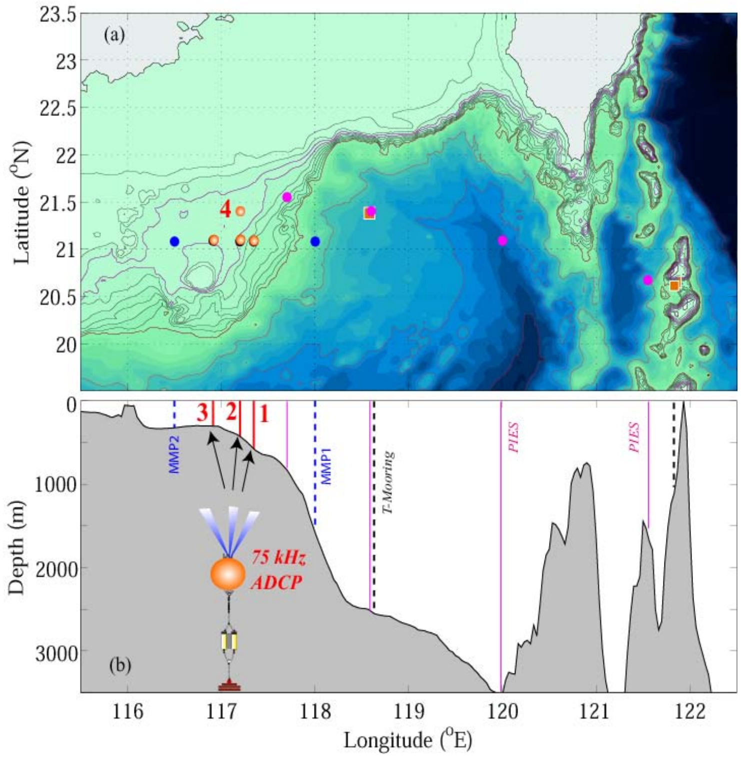

Figure 2. (a) Map of South China Sea and (b) bathymetry along 21°N. Four yellow bullets and red lines mark the locations of moored ADCPs. The configuration of the bottom-mounted 75-kHz ADCP is shown in (b). Two blue dots (vertical blue dashed lines), magenta dots (vertical magenta lines), and brown squares (vertical black dashed lines) mark the positions of McLane moored profilers (Alford), PIES (Farmer), and temperature moorings (Tang and Ramp), respectively. Labels 1–4 represent the moored ADCPs.

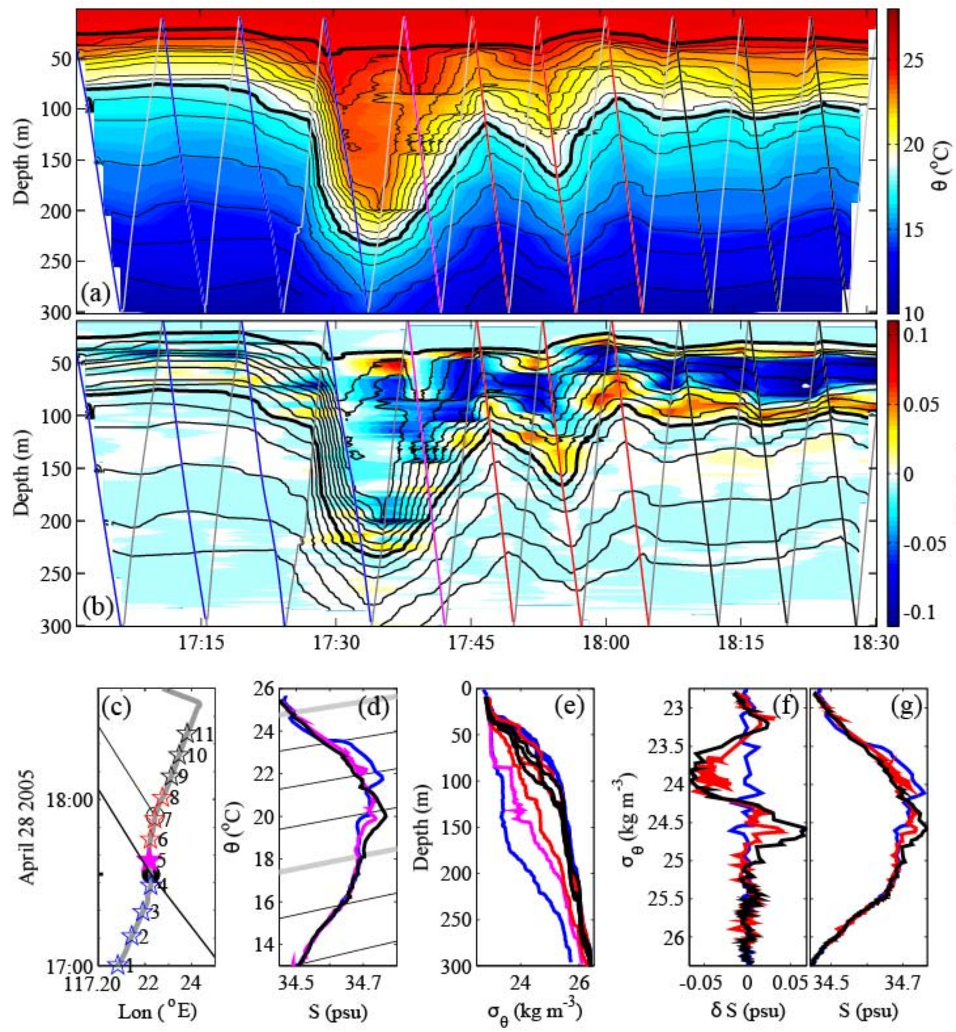

Figure 3. Water mass properties of a trapped core NLIW. (a) Depth-time variation of potential density (contours, interval = 0.2 kg m^{-3}) and potential temperature (colors). (b) Same but for salinity anomaly relative to the first CTD downcast. The zigzag vertical profiles show the trajectory of the shipboard CTD. The two thick black density contours, σ_θ = 23 and 25 kg m^{-3}, identify the range influenced by the trapped core. (c) Time and positions of yoyo CTD downcasts (stars) labeled by number of casts and color coded. The thick and open dots represent the leading NLIW and a small secondary wave. The black line represents the NLIW path. (d) Potential temperature–salinity plot for selected profiles before (blue), during (red), and after (black) NLIW passage. Thin black lines are isopycnals. Thicker grey lines are trapped core boundaries. (e) Same but for potential density profiles. (f) Same but for salinity anomaly against potential density. (g) Same but for salinity against potential density. Blue, red, and black curves in (d), (f), and (g) represent 1st, 5th, and 11th CTD downcasts, respectively. The colors of curves in (e) correspond to those of CTD tracks shown in (b).